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THE LOWER MAIN SEQUENCE OF STARS IN THE SOLAR NEIGHBORHOOD: MODEL PREDICTIONS VERSUS OBSERVATION

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Abstract. We have used the Simbad database and VizieR catalogue access tools to construct the observational color–absolute magnitude diagrams of nearby K–M dwarfs with precise *Hipparcos* parallaxes ($\sigma_\pi/\pi \leq 0.05$). Particular attention has been paid to removing unresolved double/multiple stars and variables. In addition to archival data, we have made use of nearly 2000 new radial-velocity measurements of K–M dwarfs to identify spectroscopic binary candidates. The main sequences, cleaned from unresolved binaries, variable stars, and old population stars which can also widen the sequence due to their presumably lower metallicity, were compared to available solar-metallicity models. Significant offsets of most of the model main-sequence lines are seen with respect to observational data, especially for the lower-mass stars. Only the location and slope of the Victoria-Regina and, partly, BaSTI isochrones match the data quite well.

Key words: astronomical databases: miscellaneous – stars: late type – C–M diagrams – solar neighborhood

1. INTRODUCTION

The validation of stellar theoretical models relies heavily upon the accurate determination of the location and properties of the sequences of stars in the color–luminosity diagrams. For main-sequence stars with masses above solar, most of the theoretical models are generally in line with observations. The situation is much worse when we discuss the domain of low-mass ($M < 0.8\,M_\odot$) stars. On one hand, the complexity of their spectra with molecular features dominating complicates both the calculation of stellar models and the color-temperature transformations, what leads to difficulties in determining good theoretical main-sequence lines. On the other hand, comparisons of models to data require comprehensive observations from which it would be possible to accurately locate the observational ridge lines of different metallicity. Because of the inefficiency of photometric methods to determine metallicities of M-type dwarfs, the local samples suitable for such comparisons are too modest in size. Therefore, the more generally accepted approach has been to use instead of field stars the Galactic star clusters. With this approach,

however, the advantage in having the lower main sequence of homogeneous chemical composition is often reduced by uncertainties coming from fitting procedure (distances, etc.) and the scatter within the fainter portion of the sequence due to observational limitations.

In recent years, large photometric surveys such as the Sloan Digital Sky Survey (SDSS) and the Two Micron All Sky Survey (2MASS) have proved to be superb data resources for statistical investigations of late-type dwarfs. However, accurate parallaxes are not available for the overwhelming majority of faint stars that could probe the lower-main sequence. Thus, until *Gaia* space mission becomes a reality, nearby *Hipparcos* stars still remain demanding objects.

In the paper by Kotoneva et al. (2002), *Hipparcos*-based absolute magnitudes of K dwarfs were compared with a set of theoretical isochrones for three metallicity ranges – solar, subsolar ([Fe/H] between −0.30 and −0.50) and super-solar ([Fe/H]=0.18 − 0.30). The metallicities were derived by photometric method using *Geneva* b_1 and Johnson-Cousins $(R-I)_\mathrm{C}$ or Strömgren m_1 and $(R-I)_\mathrm{C}$ colors. They found a tight relationship between luminosity, color and metallicity for K dwarfs. However, none of the isochrones tested by them in the M_V,B–V plane fitted the observational K-dwarf sequences.

Just & Jahreiß (2008) investigated the properties of the main sequence of *Hipparcos* F–K stars in the Catalogue of Nearby Stars (CNS), using the Johnson-Cousins $BV(RI)_\mathrm{C}$ data transformed to the SDSS *ugriz* filter system. Systematic differences in the shape and location of the main sequences in the *ugriz* system were found with respect to the theoretical isochrones of Padova and Dartmouth models. More recently, Bochanski et al. (2010) have derived color – absolute magnitude relations for low-mass stars using new yet unpublished $(ugriz)'$ observations and 2MASS JHK_S photometry of nearby dwarfs with known trigonometric parallax measurements. These relations have been used by the SDSS team to estimate absolute magnitudes and distances to all faint stars in their huge sample.

The aim of this paper is to make a comparison of the sequence of nearby K–M dwarfs in the (M_V, color) diagrams, based on the data available at the CDS, with theoretical solar-metallicity isochrones of various stellar models. We accept that the ridge lines, defined in the (M_V, color) diagram by stars with kinematics typical of the young to intermediate age disk, may adequately represent the locus of solar-metallicity stars. The absolute magnitudes of K–M dwarfs will be solely based on *Hipparcos* parallaxes. Our analysis in this paper is restricted to Johnson-Cousins $BV(RI)_\mathrm{C}$ photometry as in this particular system we can find the majority of accurate observational data on nearby stars and the majority of model isochrones calculated. We focus attention on the main contributors to the scatter of the observational sequence – photometric variability, unresolved binarity and measurement errors. While for information on variability and astrometric multiplicity of nearby stars we can address the *Hipparcos* survey and expanding datasets of supplementary observations, the census of spectroscopic binaries, which requires long-term radial-velocity programs, is far from being complete. Therefore, to identify new unresolved binaries among nearby K–M dwarfs, we have made use of nearly 2000 radial-velocity measurements obtained over the past decade within our CORAVEL program (Upgren, Sperauskas & Boyle 2002).

In the following section we will describe the selection of stars, refining of the samples and observational data used. Comparisons of the data to theoretical isochrones of different stellar models are demonstrated in Section 3.

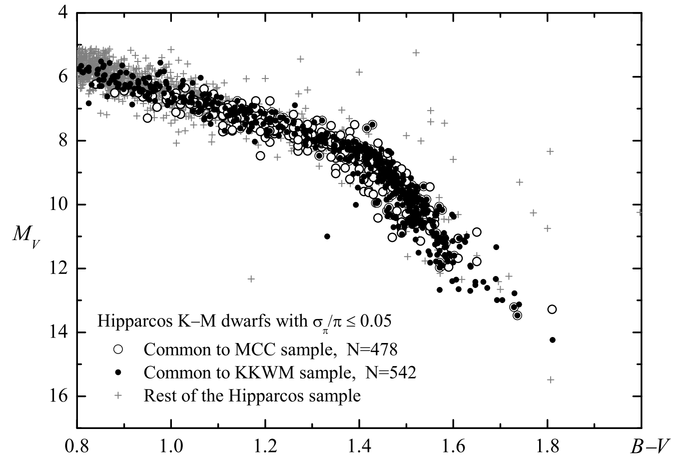

Fig. 1. M_V, B–V diagram for *Hipparcos* K–M dwarfs with $\sigma_\pi/\pi \leq 0.05$. BV photometry to plot MCC stars (open circles) and KKWM stars (solid points) is from CNS3 and Koen et al. (2010), respectively, while the rest of the stars (grey crosses) are plotted using BV data taken from the *Hipparcos* main catalog.

2. DATA AND SAMPLE SELECTION

We started with the selection of stars with precise trigonometric parallaxes from *Hipparcos* catalog (van Leeuwen 2007), which fall within the typical color and luminosity range for K and M dwarfs: B–$V > 0.80$ and $M_V \geq 5.5$ mag. A limit on parallax accuracy of $\sigma_\pi/\pi \leq 0.05$ was chosen to ensure the absolute magnitudes to be accurate to within ~ 0.1 mag, with a negligible bias introduced by the Lutz-Kelker effect. We have 1815 stars that satisfy the above criteria (Figure 1). However, for nearly half of these stars, no homogeneous and accurate photometry or supplementary data can be found in the existing databases. To have the luminosities and colors based on rigorous observational basis, we have finally chosen for further analysis two separate samples of *Hipparcos* K–M dwarfs:

(1) The McCormick sample (hereafter MCC), which constitutes stars north of declination $-30°$, selected years ago spectroscopically at the McCormick Observatory by A. N. Vyssotsky and his colleagues (for a review of their survey, see Upgren & Weis 1989). For all of these stars, the $BV(RI)_\mathrm{C}$ data are thoroughly collected at the ARI Database for Nearby Stars (CNS3, Gliese & Jahreiss (1991), with its more updated version of 1998).

(2) The sample of stars south of declination $+26°$ from the recently published catalog of homogeneous and standardized $UBV(RI)_\mathrm{C}JHK$ photometry by Koen, Kilkenny, van Wyk & Marang (2010) (hereafter KKWM).

The coverage of color – luminosity diagram by the MCC and KKWM stars with respect to the remaining *Hipparcos* stars with $\sigma_\pi/\pi \leq 0.05$ is shown in Figure 1. There was no need to apply the extinction and reddening corrections, since the stars in both samples are at distances smaller than 50 pc (the KKWM stars are within 30 pc).

All stars in the MCC sample and part of northernmost stars in the KKWM sample, which had no high-quality or any radial-velocity measurements, were tar-

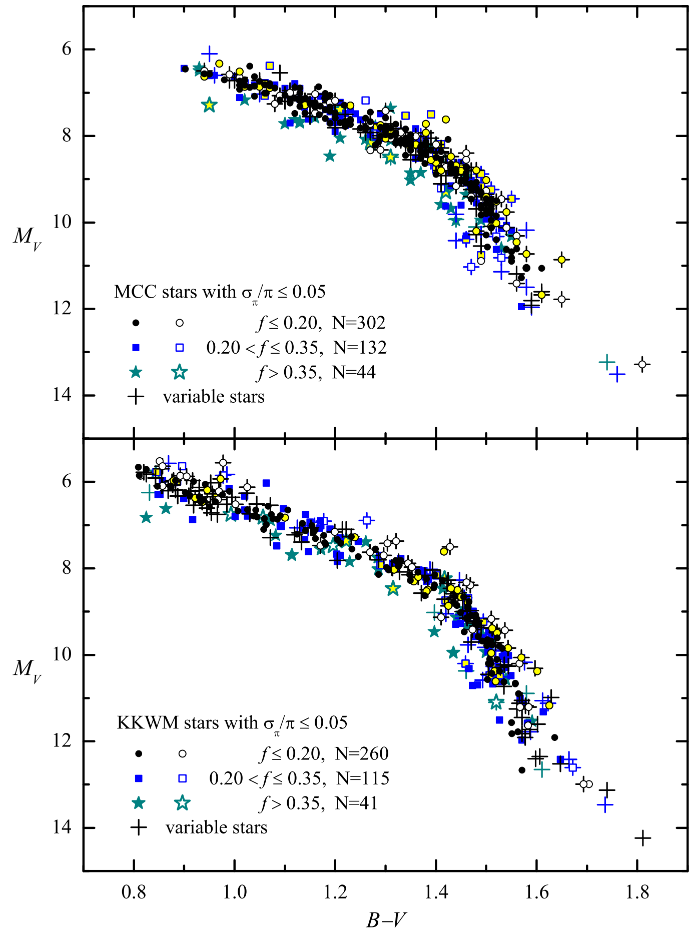

Fig. 2. M_V, B–V diagrams for K–M dwarfs with $\sigma_\pi/\pi \leq 0.05$ in the two samples. Different symbols denote different kinematic groups: young to intermediate age thin disk ($f \leq 0.20$; circles), old thin disk ($0.20 < f \leq 0.35$; squares) and thick disk ($f > 0.35$; five-sided stars). Stars showing no indication of variability or multiplicity are indicated by filled symbols, while open symbols denote known and suspected binaries (in color version, the symbols for spectroscopic binaries and radial-velocity variables are filled with yellow). Variable stars are shown by crosses (if the star is both variable and binary, a cross is overlaid by an open symbol).

gets of our decadal program of radial-velocity observations (Upgren, Sperauskas & Boyle 2002). However, 126 stars of the selected KKWM sample are still lacking good radial-velocity measurements and thus were rejected from further analysis. Thus we have 478 stars in the MCC sample and 416 stars in the KKWM sample, which satisfy the $\sigma_\pi/\pi \leq 0.05$ criterion and have radial-velocity data of satisfactory quality. Of these, 173 stars are found to be common to both samples.

In Figures 2–4 we present (M_V, color) diagrams for the two samples. To demonstrate what effect the addition of stars known or suspected to be variables, binaries and belonging to presumably metal-deficient population has on the width

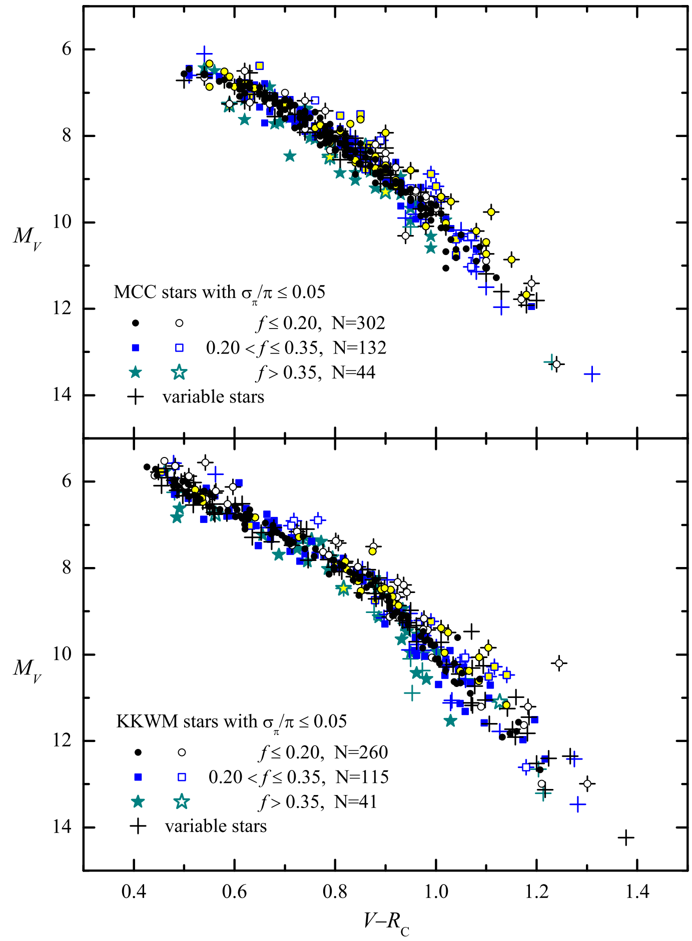

Fig. 3. M_V, V–R_C diagram for the same samples of K–M dwarfs as in Figure 2.

of the observational sequence, we plotted all these groups of stars by different symbols. We applied the so-called kinematical age parameter $f(U, V, W)$, introduced by Grenon (1987),

$$f = 1/C(a_1U^2 + a_2V^2 + a_3W^2)\,, \qquad (1)$$

to divide the stars into different populations: young- to intermediate-age thin disk ($f \le 0.20$), old thin disk ($0.20 < f \le 0.35$) and thick disk ($f > 0.35$). Here the space velocity components U, V and W are computed with the values of the Sun's motion relative the LSR $(U_0, V_0, W_0) = (-10.0, 12.2, 7.2)\,\mathrm{km\,s^{-1}}$ adopted from Schönrich et al. (2010). The normalization constant C and the coefficients a_i are adopted such that for stars on nearly circular galactic orbits the parameter f equals to orbital eccentricity. As can be seen in the figures, the stars with the thick disk kinematics are seen to lie below the sequence defined by the rest of the stars, and this is an indication of their having lower metallicity. The location of the sequence of stars with the old-thin-disk kinematics is nearly identical to that of the younger thin disk stars but differ in its larger (by 0.1 mag) scatter.

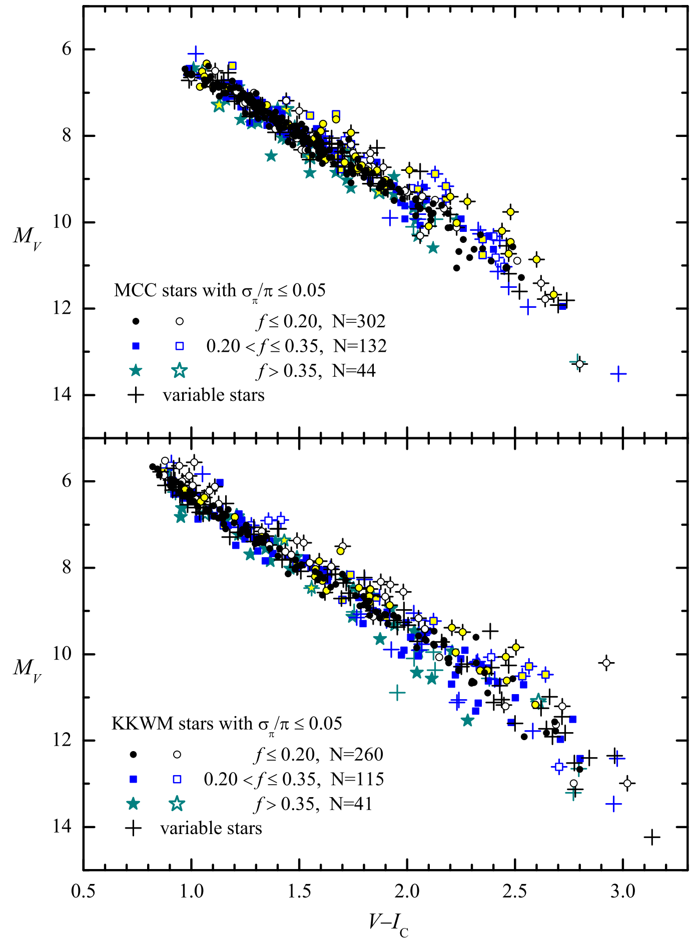

Fig. 4. M_V, V–I_C diagram for the same samples of K–M dwarfs as in Figure 2.

As one would expect, the known and suspected multiple stars tend to lie above the sequence of their single counterparts at the same color. The fraction of such stars, including those with the *Hipparcos* multiplicity flags, amounts to 30%. The spectroscopic binaries (SB) and radial-velocity variables (SB candidates) comprise 13% of the MCC sample for which our radial-velocity program is nearing completion. Contrary to the general trend, noted in the literature (e.g. Lada 2006), that the binary fraction is likely to steadily decline with spectral type, we do not see from our preliminary analysis of radial-velocity measurements a smaller fraction of SB candidates among M-type dwarfs than among K-type dwarfs (in both cases, around 10%). Based on our radial-velocity observations we report 24 new SB candidates among the MCC stars considered, in addition to those for which radial-velocity variability was noted or suspected in the literature.

The stars showing any signs of photometric variability, i.e. those found in the GCVS database (Samus et al. 2007–2011) or flagged in the *Hipparcos* catalog, constitute one third of the two samples (in Figures 2–4 indicated by crosses).

Table 1. Ridge lines for young- to intermediate-kinematic-age stars ($f \leq 0.20$): (1) MCC sample (160 stars), (2) KKWM sample (105 stars). Given in the bottom line are the standard deviations of single points from the ridge lines.

B–V	$M_V^{(1)}$	$M_V^{(2)}$	V–R_C	$M_V^{(1)}$	$M_V^{(2)}$	$M_{R_C}^{(1)}$	$M_{R_C}^{(2)}$	V–I_C	$M_V^{(1)}$	$M_V^{(2)}$	$M_{I_C}^{(1)}$	$M_{I_C}^{(2)}$
0.85		6.0	0.45		5.8		5.4	0.90		6.0		5.1
0.90		6.2	0.50		6.2		5.7	1.00	6.5	6.4	5.4	5.4
0.95	6.5	6.4	0.55	6.6	6.5	6.1	5.9	1.10	6.8	6.7	5.6	5.6
1.00	6.7	6.6	0.60	6.8	6.7	6.2	6.1	1.20	7.1	7.0	5.9	5.8
1.05	6.9	6.8	0.65	7.1	7.0	6.4	6.3	1.30	7.4	7.3	6.1	6.0
1.10	7.1	6.9	0.70	7.4	7.2	6.7	6.6	1.40	7.7	7.6	6.3	6.2
1.15	7.3	7.1	0.75	7.7	7.6	6.9	6.8	1.50	8.0	7.9	6.5	6.4
1.20	7.4	7.3	0.80	8.1	7.9	7.3	7.1	1.60	8.3	8.2	6.7	6.6
1.25	7.7	7.5	0.85	8.5	8.3	7.6	7.5	1.70	8.6	8.5	6.9	6.8
1.30	7.9	7.7	0.90	9.0	8.8	8.1	7.9	1.80	8.9	8.8	7.1	7.0
1.35	8.2	8.0	0.95	9.5	9.3	8.5	8.4	1.90	9.2	9.1	7.3	7.2
1.40	8.5	8.3	1.00	10.0	9.9	9.0	8.9	2.00	9.5	9.4	7.5	7.4
1.45	8.9	8.8	1.05	10.5	10.5	9.5	9.4	2.10	9.8	9.7	7.7	7.6
1.50	9.6	9.7	1.10	11.1	11.1	10.0	10.0	2.20	10.1	10.0	7.9	7.8
1.55	10.6	11.1	1.15		11.8		10.6	2.30	10.4	10.4	8.1	8.1
1.60		12.8	1.20		12.4		11.2	2.40	10.8	10.7	8.3	8.3
								2.50	11.1	11.1	8.5	8.6
								2.60		11.5		8.9
								2.70		12.0		9.3
s.d.	0.22	0.32		0.17	0.17	0.17	0.17		0.18	0.19	0.18	0.19

For comparison with theoretical isochrones, we removed stars which may contribute increased scatter or broadening of the observational sequence: known and probable multiple stars, variables, and stars with $f > 0.20$ which may belong to populations of subsolar metallicity. After refining the MCC and KKWM samples in this way, we are finally left with 160 and 105 stars in each sample, respectively. The ridge lines of the stellar loci in the absolute magnitude versus color planes, defined using each refined sample separately, are tabulated in Table 1 (in the column headings, superscripts (1) and (2) refer to MCC and KKWM, respectively). We note that over most of the color range the ridge lines of the KKWM sequences are systematically more luminous than those of the MCC stars, with average offsets of 0.1 mag in M_V, M_{R_C} and M_{I_C} (see Figure 5). Since systematic differences in $BV(RI)_C$ magnitudes between the MCC and KKWM data sets are found to be of 0.02–0.03 mag (in the sense that KKWM magnitudes are brighter), the much larger offsets in the color-absolute magnitude space can be explained by a larger

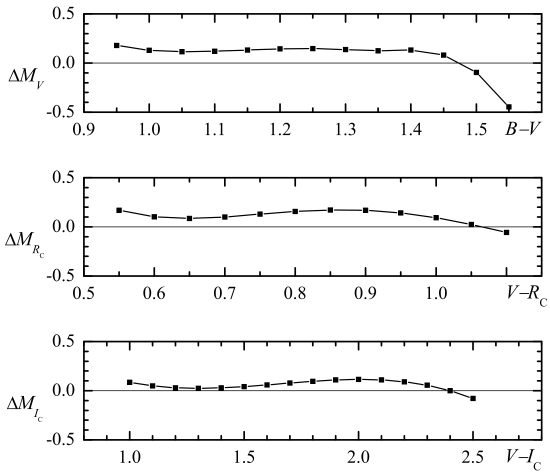

Fig. 5. Differences in absolute magnitudes between the ridge lines defined using the two samples, in the sense MCC minus KKWM.

fraction of unrecognized binaries left in the KKWM sample, which may lead to a shift of the ridge lines toward brighter absolute magnitudes. Indeed, most of the KKWM stars were not targets for our long-term radial-velocity program and the fraction of known/suspected SB among them (7%) is much less significant than that among the MCC stars (13%) covered entirely by our program.

3. COMPARISON WITH MODELS

In Figure 6 we compare a set of solar composition isochrones to the sequences of K–M dwarfs with $f \leq 0.20$, cleaned of variable and binary stars and SB candidates. The imposed cut in the kinematical age parameter f ensures that the stars belong to the young and intermediate age population and are, on average, likely to be of solar metallicity. We have tested 5 Gyr isochrones (the effect of age is minor in the K–M dwarf range) of the following stellar evolution models:

(1) Dartmouth (Dotter et al. 2008);
(2) Padova (Marigo et al. 2008);
(3) BaSTI (Cordier et al. 2007);
(4) Victoria-Regina (VandenBerg et al. 2006);
(5) Yonsei-Yale Y^2 (Demarque et al. 2004) with the older (GDK, Green et al. 1987) magnitude/color transformations;
(6) Geneva (Lejeune & Schaerer 2001);
(7) Siess et al. (2000).

In the M_V,B–V diagram of Figure 6, we also show the empirical relation from the calibrations by Schmidt-Kaler (1982), and, in the M_V,V–$I_{\rm C}$ diagram, the fiducial line of the solar-metallicity open cluster M67, taken from Sandquist (2004) but extended to the redder colors (V–$I_{\rm C} \geq 1.6$) using photometric data from the WEBDA Data Base. To aid visualization, we have plotted in the figure the sequences of the MCC and KKWM stars rather than their ridge lines. Note that photometry for 108 MCC stars not common to the KKWM sample comes from the CNS3 database, while for 52 stars common to both samples and for the rest 53 KKWM stars is taken from KKWM. Therefore, plotted in the figure are comparable numbers of stars representing the two sources of $BV(RI)_{\rm C}$ photometry.

We conclude by Figure 6 that, with a few exceptions, most of the isochrones provide a satisfactory fit to the dwarfs of spectral types earlier than K7 (B–V<1.3), but fail to reproduce the stellar locus of the less luminous dwarfs. In the region of M stars (B–V≥1.4), some isochrones diverge from the main sequence by more than 1 mag. Most appropriate are the Victoria-Regina isochrones, which provide a good fit to the shape of the main sequence down to the limit of their models (around M5), and the BaSTI isochrones, matching the locus of K dwarfs well, especially in the M_V,B–V plane. The BaSTI colors V–$R_{\rm C}$ and V–$I_{\rm C}$ at the reddest end (around K8–M0), however, do not correctly match the data. In the M_V versus V–$R_{\rm C}$ and V–$I_{\rm C}$ planes, the Dartmouth models and isochrones by Siess et al. (2000) also fit the data, but only down to spectral type K8. There is also a general agreement between the sequence of field K–M dwarfs and the fiducial line of M67.

In summary, the samples of nearby K–M dwarfs show that there is a clear problem in fitting most of the stellar models to low mass stars. The Victoria-Regina isochrones (VandenBerg et al. 2006) with empirically constrained color-temperature relations by VandenBerg & Clem (2003) appear to be the only models

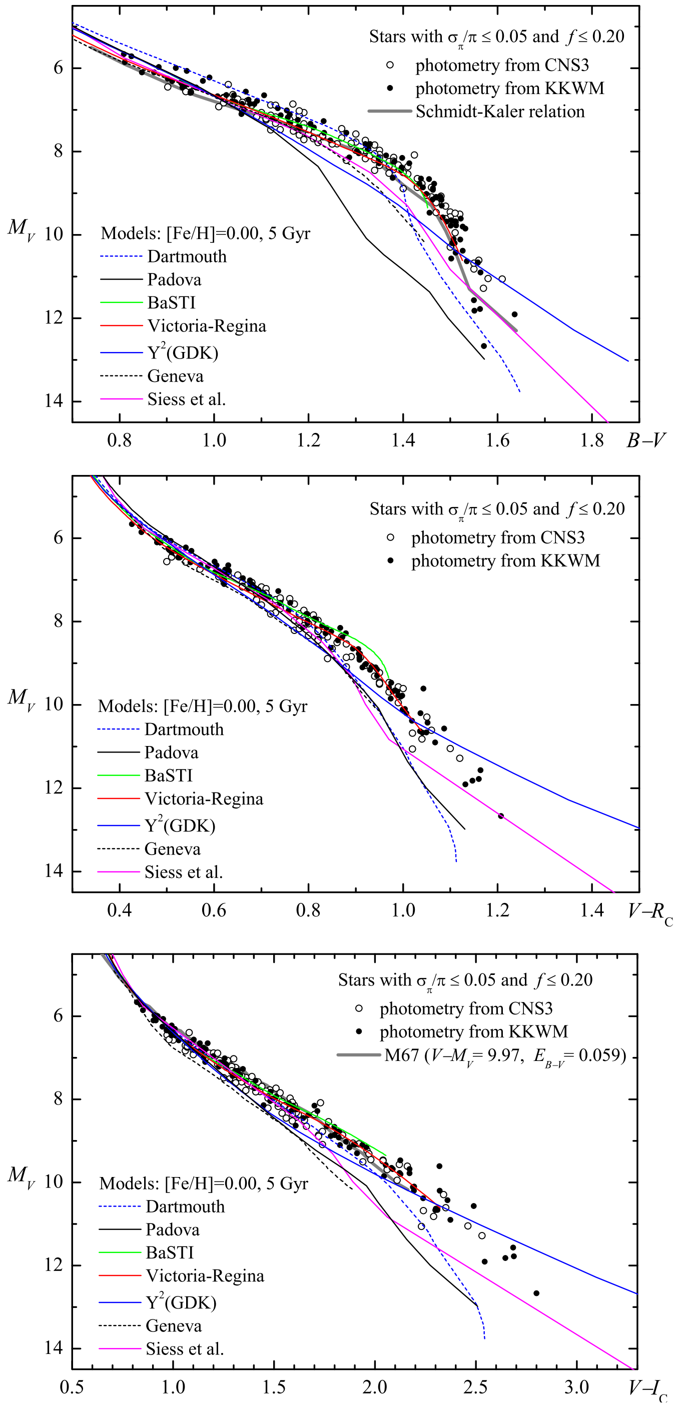

Fig. 6. Comparison of the observational (M_V, color) sequences for K–M dwarfs with $f \le 0.20$ to solar metallicity theoretical isochrones of different models.

which are entirely consistent with the observed loci of lower main-sequence stars in the $BV(RI)_{\rm C}$ system.

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